

Cosmic Structure and Dynamics of the Local Universe

Francisco-Shu Kitaura^{1*}, Pirin Erdoğdu², Sebastián E. Nuza¹, Arman Khalatyan¹,
Raul E. Angulo³, Yehuda Hoffman⁴ and Stefan Gottlöber¹

¹ *Leibniz-Institut für Astrophysik (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany*

² *Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*

³ *Max-Planck Institut für Astrophysik (MPA), Karl-Schwarzschildstr. 1, D-85748 Garching, Germany*

⁴ *Racah Institute of Physics, Hebrew University, Jerusalem, Israel*

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ABSTRACT

We present a cosmography analysis of the Local Universe based on the recently released Two-Micron All-Sky Redshift Survey (2MRS). Our method is based on a Bayesian Networks Machine Learning algorithm (the KIGEN-code) which self-consistently samples the initial density fluctuations compatible with the observed galaxy distribution and a structure formation model given by second order Lagrangian perturbation theory (2LPT). From the initial conditions we obtain an ensemble of reconstructed density and peculiar velocity fields which characterize the local cosmic structure with high accuracy unveiling nonlinear structures like filaments and voids in detail. Coherent redshift space distortions are consistently corrected within 2LPT. From the ensemble of cross-correlations between the reconstructions and the galaxy field and the variance of the recovered density fields we find that our method is extremely accurate up to $k \sim 1 \ h\text{Mpc}^{-1}$ and still yields reliable results down to scales of about $3\text{--}4 \ h^{-1} \text{Mpc}$. The motion of the local group we obtain within $\sim 80 \ h^{-1} \text{Mpc}$ ($v_{\text{LG}} = 522 \pm 86 \text{ km s}^{-1}$, $l_{\text{LG}} = 291^\circ \pm 16^\circ$, $b_{\text{LG}} = 34^\circ \pm 8^\circ$) is in good agreement with measurements derived from the CMB and from direct observations of peculiar motions and is consistent with the predictions of ΛCDM .

Key words: (cosmology:) large-scale structure of Universe – galaxies: clusters: general – catalogues – galaxies: statistics

1 INTRODUCTION

The Local Universe (LU) harbours the link between the early Universe and our present day cosmic environment. A profound analysis of its cosmic structure is thus essential to gain insight into the processes which lead to structure formation in our surroundings and ultimately to our own Galaxy. This is one of the main goals performing constrained simulations of the LU (see e. g. Bistolas & Hoffman 1998; Kravtsov et al. 2002; Klypin et al. 2003). To carry out this kind of studies one needs first to recover the initial fluctuations which gave rise to the galaxy distribution we observe in our neighbourhood. However, such a task implies various complications since in general a galaxy redshift survey provides a discrete sample of biased matter tracers which are degraded by observational effects like a radial selection function, due to a magnitude limit cut, and redshift-space distortions caused by peculiar motions with respect to the Hubble flow (see discussion in Platen et al. 2011, and refer-

ences therein). For very nearby structures one may use measurements of radial velocities to partially avoid these problems (see e. g. Zaroubi et al. 1999). However, one still needs to trace the observations back in time unfolding gravity which couples matter on different scales in a nonlinear and nonlocal way. While linear approaches are useful to reconstruct the baryon acoustic oscillations signal on very large scales (Eisenstein et al. 2007), they fail on small scales when the nonlinear regime becomes relevant. One may solve the boundary problem of finding the initial Lagrangian positions of galaxies by minimizing an action as suggested in different works (see e. g. Peebles 1989; Nusser & Branchini 2000; Branchini et al. 2002; Brenier et al. 2003). The determination of the initial conditions (and hence of the displacement field) automatically yields estimates on the peculiar velocity field (see also Mohayaee & Tully 2005; Lavaux et al. 2008, in addition to the previously cited works). The mismatch in the measurement of the Local Group (LG) velocity from the cosmic microwave background (CMB) (Hinshaw et al. 2009) and from the matter distribution in the LU (see Bilicki et al. 2011, and references therein) together with the recent claims

* E-mail: kitaura@aip.de, Karl-Schwarzschild fellow

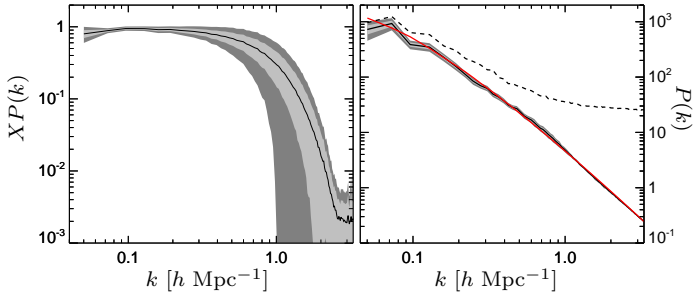


Figure 1. *On the left:* Normalised cross-power spectra $XP(k) \equiv \langle |\hat{\delta}^{\text{rec}}(\mathbf{k}) \hat{\delta}^{\text{gal}}(\mathbf{k})| \rangle / (\sqrt{P^{\text{rec}}(k)} \sqrt{P^{\text{gal}}(k)})$ between the galaxy overdensity and the reconstructed density field with 1 and 2 sigma contours (light and dark shaded regions, respectively). *On the right:* power spectrum of the galaxy field $P^{\text{gal}}(k)$ (dashed curve), linear Λ CDM power spectrum (red curve), mean of the 100 reconstructed linear power-spectra of the initial field (black curve) with 1 and 2 sigma contours (light and dark shaded regions, respectively).

on large-scale flows which could challenge the standard cosmological model (or give some hints on the initial perturbations of the Universe, see e. g. Kashlinsky et al. 2008; Watkins et al. 2009) stresses the need for more accurate studies of the local dynamics. It should be noted that the number of solutions compatible with the observations is degenerate due to shell crossings and redshift-space distortions (see e. g. Yahil et al. 1991). Moreover, the approaches mentioned above do not provide yet the initial fluctuation field. At this point another assumption needs to be made on the statistics of the initial fluctuations. From these arguments it should be clear that the estimation of the initial conditions corresponding to a galaxy distribution in redshift-space has a stochastic nature which should be treated in a statistical way to accurately model the propagation of uncertainties. For this reason we suggest to extend the Bayesian works based on linear Gaussian fields (see the pioneering works during the 90s: Hoffman & Ribak 1991; Zaroubi et al. 1995; Fisher et al. 1995; van de Weygaert & Bertschinger 1996; Zaroubi et al. 1999; Schmoldt et al. 1999) and apply a Bayesian Networks Machine Learning approach including a nonlinear and nonlocal model for structure formation providing an ensemble of reconstructed initial and final density and peculiar velocity fields (see Kitaura 2012). This ensemble of solutions enables us to estimate in a realistic way the uncertainties in the reconstruction and cross-check the accuracy of the method with the observations, improving previous work concerning single “optimal” solutions limited to linear Eulerian or Lagrangian perturbation theory.

2 DATA, METHOD AND RESULTS

The analysis presented here is based on version 2.3 of the recently released 2MASS redshift survey (2MRS), $K_s = 11.75$ catalogue (Huchra et al. 2012). The 2MRS survey is unique in its sky coverage (91%) and uniform completeness (97.6%) only limited near the Galactic plane (*the Zone of Avoidance* (ZoA), where $|b| < 5^\circ$ and $|b| < 8^\circ$ near the Galactic centre). The ZoA could be sampled with a Poissonian likelihood describing the counts-in-cells of the galaxy distribu-

tion which would be limited to a coarse grid resolution (see e. g. Kitaura et al. 2010). To incorporate a mask treatment within a particle based reconstruction method like ours, we would need to sample mock galaxies (or haloes) according to our structure formation model following schemes like the one proposed in Scoccimarro & Sheth (2002), which is out of scope in this work. For the time being, we fill the ZoA with random galaxies generated from the corresponding longitude/distance bins in the adjacent strips (Yahil et al. 1991). The method is robust for the width of the 2MRS mask and has been thoroughly tested (for details see Erdoğan et al. 2006, and references therein). According to recent studies, the LG velocity should be independent of the treatment of the mask (see Bilicki et al. 2011). Another essential ingredient is the radial selection function f^{sel} arising from the magnitude limit cut of the galaxy redshift survey. Here we derive f^{sel} from the 6 degree field galaxy survey (6dFGS) luminosity function (Jones et al. 2006), imposing a magnitude limit cut which corresponds to the one of 2MRS. However, we note that the choice of the particular derivation of f^{sel} is not crucial (see Branchini et al. 2012). The behaviour of f^{sel} can be further checked in the power-spectra of the reconstructed initial fluctuations $P^{\text{rec}}(k)$ (see below). Finally, we compress the *fingers-of-god* after identifying them with a *friends-of-friends* algorithm taking into account the ellipsoidal distribution along the line-of-sight of groups of galaxies due to virial motions (see Tegmark et al. 2004). The resulting catalog provides the Cartesian three-dimensional positions of the 2MRS galaxies in Supergalactic coordinates including coherent redshift-space distortions.

This catalog is used as an input for the KIGEN-code which relies on 2LPT to describe structure formation (see recent works on this subject: Kitaura & Angulo 2011; Kitaura et al. 2011; Jasche & Wandelt 2012; Kitaura 2012, and references therein). We assume Gaussian initial density fields with a variance determined by the cosmological parameters from the concordance Λ CDM-cosmology as provided by the Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) (see table wmap7+bao+h0 in Komatsu et al. 2011). In this study we consider the data within a comoving box of $160 h^{-1}$ Mpc side (comprising about 30,000 galaxies). Coherent redshift-space distortions are consistently modeled with 2LPT (beyond the Kaiser limit; Kaiser 1987) by adding a radial term to the Eulerian real-space position $\mathbf{x} = \mathbf{q} + \mathbf{\Psi}$, where \mathbf{q} is the Lagrangian position of the matter tracers at the initial conditions and $\mathbf{\Psi}$ is the displacement field according to 2LPT. The redshift-space position \mathbf{s} of each matter tracer is thus given by the following equation in our model $\mathbf{s} = \mathbf{q} + \mathbf{\Psi} + \mathbf{v}_r$, with $\mathbf{v}_r \equiv (\mathbf{v} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}/(Ha)$, where \mathbf{v} is the full three dimensional 2LPT velocity field, $\hat{\mathbf{r}}$ is the unit sight line vector, H the Hubble constant and a the scale factor. The KIGEN-code samples the initial fluctuations according to the set of Lagrangian test particles $\{\mathbf{q}\}$ which under 2LPT yields a distribution in Eulerian redshift-space $\{\mathbf{s}\}$ compatible with the observed galaxies $\{\mathbf{s}_G\}$. We use in each constrained 2LPT simulation 256^3 test particles and compute the displacement field on a grid of 128^3 cells with a resolution of $l_c = 1.25 h^{-1}$ Mpc. Particles which are closer than l_c to a galaxy are considered to be “friends” of that galaxy and their Lagrangian positions are used as constraints to determine the initial Gaussian fluctuations (for more details on the method we refer to Kitaura 2012). We

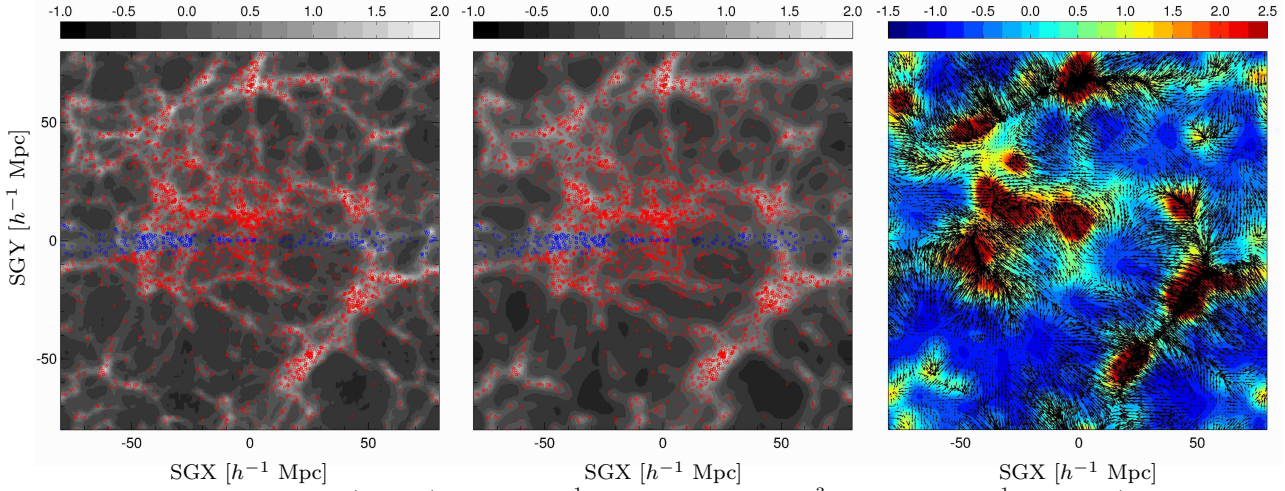


Figure 2. Supergalactic XY-plane (SGZ=0) with $\sim 20 h^{-1}$ Mpc thickness of a 128^3 grid with $160 h^{-1}$ Mpc side (resolution of $1.25 h^{-1}$ Mpc): *left panel*: logarithm of the reconstructed density field $\ln(2 + \delta^{\text{rec}})$ (one sample belonging to the highly correlated subsample of 21 reconstructions which have a cross-correlation with the galaxy overdensity better than 1 sigma at scales $\geq 3.5 h^{-1}$ Mpc) with overplotted observed galaxies in red and augmented ones in blue; *middle panel*: logarithm of the mean density field of all 100 samples $\ln(2 + \langle \delta^{\text{rec}} \rangle)$, *right panel*: $v_x - v_y$ velocity field with the underlying galaxy overdensity field after $3.5 h^{-1}$ Mpc Gaussian smoothing. The length of the arrows is proportional to the average speed at that location.

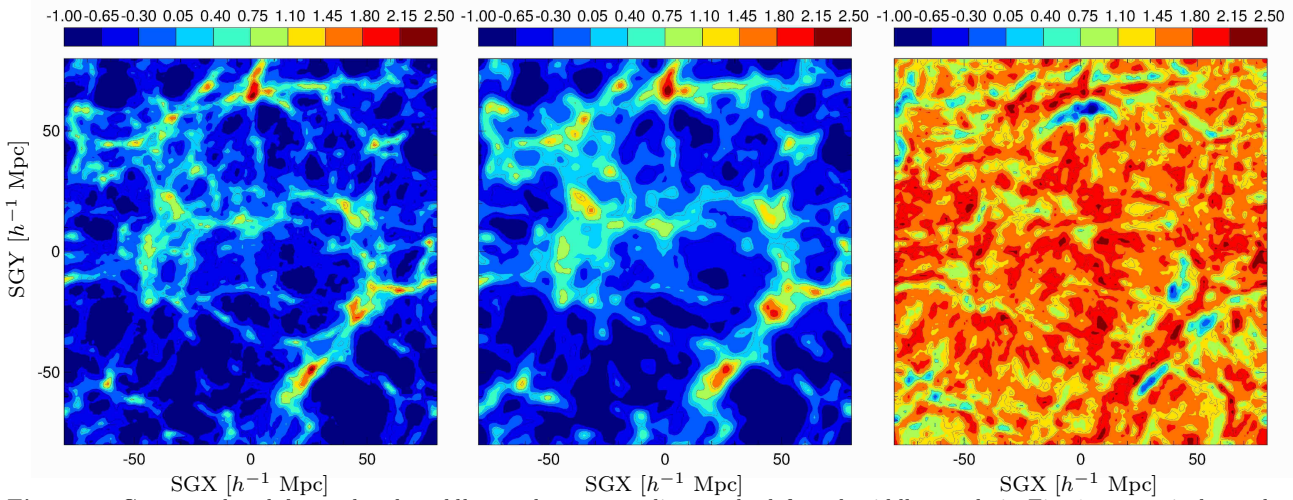


Figure 3. Contour plot: *left panel* and *middle panel*: corresponding to the left and middle panels in Fig. 2, respectively; *right panel*: logarithm of the signal-to-noise ratio of the mean density field ($S/N \equiv \langle \delta^{\text{rec}} \rangle / \sigma(\delta^{\text{rec}})$) in each cell from all samples in the same slice as the other panels.

account for selection function effects and shot noise in our reconstruction by assigning in each iteration a weight to every particle according to a Poisson sample of the expected mass given by the inverse of f^{sel} evaluated at the distance of the corresponding galaxy. We consider for our analysis a set of 100 constrained 2LPT reconstructions of the LU, with the corresponding initial conditions and peculiar velocity fields. Our approach searches for Gaussian fields with a given prior power-spectrum (red curve in the right panel of Fig. 1). In Bayesian terms, the posterior from which we sample the initial density fluctuations is based on the above mentioned prior and a Poissonian likelihood for the test particles which we assume to be unbiased matter tracers. However, as the data are sparse and noisy and have a moderate galaxy bias (see e. g. Lavaux 2010), the posterior resulting from weighting the likelihood with the prior yields closely unbi-

ased power spectra. This is also indicating that our treatment of the selection function is accurate. Otherwise a few modes on the very large scales would show a clear excess of power as we found in our tests. We note, that further studies should be done including a proper treatment of galaxy bias. It is difficult to do a fair comparison between the density field and the galaxy field due to bias and selection function effects. However, we find a remarkable correlation up to $k \sim 1 h \text{ Mpc}^{-1}$ between the constrained 2LPT simulated overdensity field ($\delta_i^{\text{rec}} \equiv N_i^{\text{part}} / \overline{N}^{\text{part}} - 1$, with N_i^{part} : test particles number count per cell i , $\overline{N}^{\text{part}}$: mean) and the one directly computed from the galaxies ($\delta_i^{\text{gal}} \equiv N_i^{\text{gal}} / (\overline{N}^{\text{gal}} f_i^{\text{sel}}) - 1$, with N_i^{gal} : galaxy number count per cell i , $\overline{N}^{\text{gal}}$: expected mean) (see left panel). The correlation does not vanish until $k \approx 2.5 h \text{ Mpc}^{-1}$. This result is supported by the Supergalactic plots in Fig. 2 (left and middle panels), which show

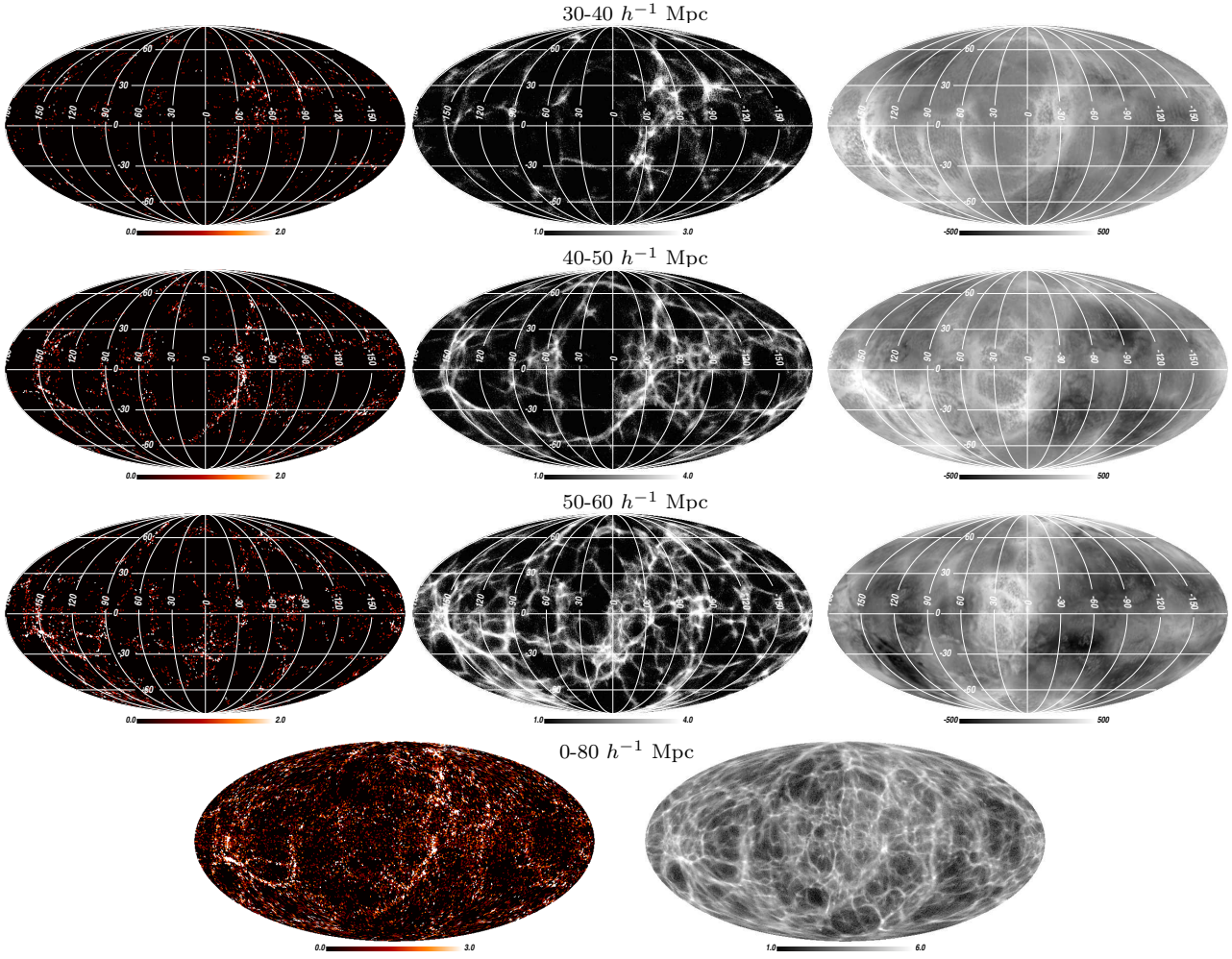


Figure 4. Mollview plots in Galactic coordinates using HEALPix of the number counts of spectroscopic 2MASS galaxies. *On the left* with $n_{\text{side}} = 64$ in different comoving distance ranges. *The middle panels* (right panel on the bottom) show the corresponding logarithm of number counts of particles from the reconstructed density field (one sample belonging to the highly correlated subsample) using $n_{\text{side}} = 128$. *The right panels* (not present on the bottom) show the corresponding radial velocities averaged on each pixel with the number counts of particles in km s $^{-1}$ using $n_{\text{side}} = 128$. We note that the Galactic longitudes l_{gal} have a shift of 360° .

how the nonlinear structures are accurately traced along the distribution of galaxies at scales of $2\text{--}5 h^{-1}$ Mpc, even in regions with only of a few data points. The right panel shows the corresponding peculiar velocity field to a high level of detail demonstrating the formation of caustics in the high galaxy number density regions. We expect to get better results using an improved structure formation model, especially in low density regions where 2LPT is known to perform worse (see e. g. Bernardeau et al. 2002). We leave such a work for future studies. We have checked that systematic discrepancies between the reconstructed 2LPT density field and the galaxy field are rather small (we obtain a statistical correlation coefficient of about 0.96 for the log-density field taking the volume of $(160 h^{-1} \text{ Mpc})^3$) when one allows for an effective, linear bias combined with a Poisson sampling of the field that accounts for both galaxy bias and the failure of 2LPT on small scales. A way of improving this would consist on using the halo model as it was suggested by (Scoccimarro & Sheth 2002). We use the ensemble of constrained simulations to compute the mean and standard deviation in each cell (see middle and right panel in

Fig. 3). This gives us an estimate of the uncertainty in the position of the density peaks. If we look at Coma which central region has an extension of a few h^{-1} Mpc and is located at $(0, 69, 11) h^{-1}$ Mpc in SG-coordinates, we find that the uncertainty in the position is only of about $2\text{--}3 h^{-1}$ Mpc. The major uncertainties concern the extension around very massive structures being overall very robust (with $S/N > 1$ in most of the cells, see right panel). The quality of the reconstruction can be further assessed in the Mollview plots of Fig. 4 performed with HEALPix (Górski et al. 2005). Here the data (left panels) can be compared to the reconstruction (middle and right panels) for different redshift slices. The accuracy of the reconstruction is very apparent to the level of connecting small number of galaxies through tiny filaments. On the right panels the radial peculiar velocity field shows similar patterns than in linear theory (see Erdoğan et al. 2006, for a careful description of the different structures), however reconstructing a significantly more complex structure. The bottom panels in Fig. 4 show the full projection on the sky to a distance of $80 h^{-1}$ Mpc. The data (left panel) have a very noisy appearance while the reconstruction (right

panel) unveils the corresponding cosmic web.¹ Fig. 5 shows our calculations of the LG velocity by evaluating the reconstructed velocity field at the center of the box. The uncertainties in the estimation of the velocity field mainly depend on the randomness of the initial fluctuations and the shot noise due to the discrete galaxy sample including selection function effects. As it was shown in Kitaura et al. (2011) 2LPT is extremely accurate in the determination of the peculiar velocity field. We therefore do not expect significant systematic errors beyond the fact that we are considering the matter inside a volume of $(160 h^{-1} \text{ Mpc})^3$. We repeat our calculations for a subsample of extremely highly correlated reconstructions with the galaxy field finding consistent results and hence demonstrating the robustness of our calculations.

3 DISCUSSION AND CONCLUSIONS

We have performed a Bayesian cosmography analysis of the LU with the 2MRS galaxy redshift survey. Our approach leads to more accurate estimates of the dynamics in the LU with respect to previous ones which either assume linear Eulerian relations (see e. g. Fisher et al. 1995; Erdoğan et al. 2006; Bilicki et al. 2011) or linear LPT (see e. g. Lavaux et al. 2010). There are still a number of issues which should be further investigated, as for instance the impact of galaxy bias or full nonlinear evolution on the dynamics. To extend the study presented here to larger volumes one should include a treatment of the so-called *rocket-effect* as it becomes more relevant in regions where the selection effects are more severe, i. e. at larger distances to the observer (see e. g. Branchini et al. 2012). This effect could be iteratively corrected by re-computing the selection function at the galaxy estimated real-space position at each reconstruction step in our algorithm following the pioneering work of Yahil et al. (1991). Nevertheless, it is worth noting that we model for the first time nonlocal and nonlinear effects in the calculation of the local cosmic flow including the tidal field component (within 2LPT). To perform higher order LPT it is essential to get accurate estimates of the linear component of the density field as it was pointed out in Kitaura & Angulo (2011); Kitaura et al. (2011). This is done in this work in a self-consistent way by iteratively sampling the Gaussian fields compatible with the data within 2LPT. In particular, we map local structures like the Local Void, the Local Supercluster (Virgo), the Coma Cluster, the Perseus Pisces Supercluster and the Great Attractor (Hydra and Centaurus) in great detail. Our results show a wide range of LG velocity amplitudes (from about 350 to 600 km s^{-1}). These findings indicate that the propagation of uncertainties is non-trivial and hence, the need for more studies including a nonlocal and nonlinear self-consistent treatment of gravity on different volumes (as indicated in Erdoğan & Lahav 2009). The lower speeds than the ones from the CMB (16-18% lower) found in our study and the angle separation of about $20^\circ \pm 10^\circ$ indicate that the dipole has not converged yet considering the matter up to distances

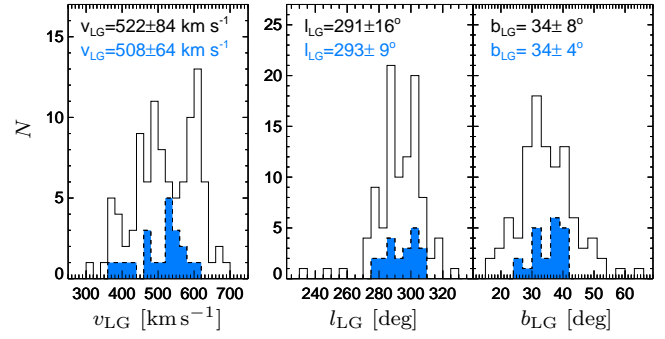


Figure 5. Histograms for the speed v_{LG} and the direction (l_{LG}, b_{LG}) (Galactic) of the Local Group for the 100 reconstructed samples (black lines) and the highly correlated subsample (see caption in Fig. 4) (dashed lines filled in blue color code). The corresponding means and 1 sigma deviations are indicated.

of about $80 h^{-1} \text{ Mpc}$. This is in good agreement with ΛCDM which predicts the dipole to have reached at those scales about 70 to 80% of its total amplitude (see e. g. Lavaux et al. 2010; Bilicki et al. 2011). Interestingly, the amplitude and direction of the LG velocity we find is compatible within the (1 sigma) error bars with the direct observation of peculiar motions (see Courtois et al. 2012). Our results are also consistent (within 2 sigma) with previous studies (see e. g. Erdoğan et al. 2006; Lavaux et al. 2010; Bilicki et al. 2011). We hope that the outcome of works like the one presented here leads to a variety of applications ranging from cosmic web analysis, environmental studies and signal detections like the kinematic Sunyaev-Zel’dovich effect, to accurate constrained simulations enabling us to improve our understanding on structure formation in the LU.

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¹ The figures are available in high resolution at: www.aip.de/People/fkitaura/

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